

COLLISIONAL AND DYNAMICAL PROCESSES IN MOON AND PLANET FORMATION  
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We report research on a variety of dynamical processes relevant to the formation of planets, satellites and ring systems. Our main focus has been on studies of accretionary formation of early protoplanets using a numerical model, structures and evolution of ring systems and individual bodies within planetary rings (Davis et al., Science 224, 1984; Weidenschilling et al., in Planetary Rings, p. 67, 1984) and theories of lunar origin (Weidenschilling et al., in Origin of the Moon, p. 731, 1986; Hartmann, in Origin of the Moon, p. 579, 1986).

Our earlier work on planetary accretion has been in the context of gas free accretion. However, a significant area of recent Planetary Science Institute research concerns the effects of gas drag and resonances on the accretion of planets. While at present there does not appear to be a strong requirement for the presence of gas during formation of the terrestrial planets, there is increasing support for the idea that the giant planets formed by accumulation of massive solid cores that eventually captured gas from the solar nebula (Bodenheimer and Pollack, Icarus 67, 391, 1986). Models for accretion that do not consider affects of gas drag on planetesimal dynamics are unable to produce such cores on reasonable timescales.

Weidenschilling and Davis (Icarus 62, 16, 1985) under a separately funded program showed that orbital decay due to gas drag and resonant gravitational perturbations lead to stable trapping of planetesimals at commensurability resonances with a planetary embryo. The synergistic effect of drag and resonances allows a planetary embryo to pump up eccentricities of smaller planetesimals to values much larger than those due to random encounters. Eccentricities of a few  $\times 10^{-2}$  are induced for plausible nebular models, independent of the sizes of planetesimals. The close spacing of resonances ensures that different resonant orbits overlap, and cross the non-resonant orbits between them. The high relative velocities,  $\sim 1$  km/sec, cause comminution of the planetesimals. This process could allow an early-formed planetary embryo to inhibit the growth of potential rivals, and to dominate the zone covered by overlapping resonances (up to the 2/3 exterior resonances). That scenario alleviates the tendency of numerical accretion models to produce too many, closely-spaced small planets. Weidenschilling and Davis noted that if resonances were completely effective for inhibiting accretion, the spacing of planetary orbits would approximate their actual values. However, whether this process would yield a single embryo or several in a given zone depends on details of the size distribution and its rate of change, impact strengths of planetesimals, nebular structure, etc. Detailed numerical simulations are needed to determine the likely range of outcomes.

We are examining in this program the range of outcomes by numerical simulations of accretion with resonance effects due to an early-formed planetary embryo. Our approach uses a variant of the method of Spaute et al., (Icarus 64, 139, 1985). We have been aided in this effort by collaboration with Dr. Spaute, who has been in residence at PSI during 1985-86. The simulation computes the outcome of collisions among

planetesimals in as many as 50 narrow radial zones spanning a range of semimajor axis; bodies in different zones interact when their eccentricities allow their orbits to cross. This spatial resolution allows explicit inclusion of e-pumping at discrete resonances in specific zones, and the transfer of mass between zones by collisions and drag. Resonance effects --  $de/dt$ , size limits for trapping, resonance widths, etc. -- are parameterized from results of Weidenschilling and Davis (1985) and Weidenschilling (1986, submitted to *Gerland-Beiträge zur Geophysik*).

These simulations involve a determination of the probability density for collisions between bodies in overlapping orbits, with a Monte Carlo determination of the specific interactions. Collisional outcomes, ranging from accretion to complete disruption, depend on impact speeds and the assumed mechanical properties of the planetesimals. In addition, the radial movement of matter between zones due to secular decay of planetesimal orbits is accounted for. A major limitation at present is the lack of detailed information on the distributions of sizes and orbital elements of the planetesimals. Due to the complexity of the program, only mean values for the size, eccentricity, and inclination are computed in each radial zone. However, these quantities can be weighted (e.g., according to mass or cross-sectional area, as appropriate) for assumed power-law size distributions.

Fig 1 shows the results for one such simulation. An embryo of mass  $3 \times 10^{-7} M_{\odot}$  (one Mars mass) is assumed present at 1 AU, and the effects of its perturbations on a swarm of planetesimals with initial mean radius 1 km is computed. After a model time of 550 yr, eccentricities have increased significantly at resonances. The mean size has decreased sharply at those locations due to collisional comminution, while accretion occurs in the relatively quiescent zones between the non-overlapping low-order resonances. The evolution of eccentricities is dominated by resonant perturbations, so any uncertainties in the effects of mutual gravitational stirring of planetesimals are unimportant to the outcome. Some low-order information on the size distribution can be obtained from the number of shattering events that yield power-law fragment distribution; several tens of percent of the total swarm has been processed through such events and can be brought to the embryo for accretion. Future efforts will be directed toward computing more detailed size distributions.

Hartmann, also working with our visiting scientist, D. Spaute, has undertaken an investigation of the accretional evolution in a circumterrestrial (or generally, circumplanetary) cloud of debris. Hartmann and Spaute visualize the creation of a chaotic, spheroidal or flattened cloud by an unspecified process (such as giant impact?) in a "stage 1." They then investigate "stage 2," the collisional evolution that follows from specified parameters of mean  $e$ ,  $i$ , material properties, etc. in the cloud. This study used a variant of the accretion numerical model by Spaute et al. (1985) which models growth at different distances from a primary. For this work, Hartmann has updated and modified the treatment of some of the material parameters based on our experimental results. Preliminary results

suggest the very rapid collapse of a chaotic cloud into a flattened ring, faster growth on the inner edges of the cloud, and a transition from fragmentation to accretion as energy dissipation reduces collision velocities. Thus, if a giant impact threw out a cloud of debris, accretion might occur first in the inner part of the cloud. A sufficiently large satellite accreted inside the synchronous point would spiral inward, but such a satellite accreted just beyond the synchronous point would spiral outward, sweeping up the rest of the debris. This could account for lunar formation.

We are currently reviewing our numerical models for calculating collisional outcomes and orbital stirring due to gravitational encounters. These algorithms were developed about ten years ago and while they have been updated occasionally, there has never been a comprehensive review of them in light of new experimental and theoretical results. We have undertaken a complete review and updating of these models. In particular we will use the much more extensive collisional database that now exists (e.g. review by Fujiwara, Mem. Soc. Astron. Ital. 57, No. 1, 47, 1986) and new scaling relationships (Holsapple and Housen Mem. Soc. Astron. Ital. 57, No. 1, 65, 1986; Housen et al., JGR 88, 2485, 1983) to revise as needed the predictions of our collisional outcome model. Recent work on gravitational stirring by Stewart and Wetherill (LPSC XVII Abstracts, 827) 1986, Carusi et al. (BAAS 18, No. 3, 776, 1986) and Wetherill and Cox (Icarus 63, 290, 1985) will be used to test and improve as needed our present algorithm for modeling this very important effect for planetary accretion.

